UCRL-JRNL-202033

On the Contribution of Gamma Ray Bursts to the Galactic Inventory of Some Intermediate Mass Nuclei

J. Pruet, R. Surman, G. C. McLaughlin

January 27, 2004

Astrophysical Journal Letters

On the Contribution of Gamma Ray Bursts to the Galactic Inventory of Some Intermediate Mass Nuclei

Jason Pruet[1], Rebecca Surman[2,3] & Gail C. McLaughlin[3]

ABSTRACT

Light curves from a growing number of Gamma Ray Bursts (GRBs) indicate that GRBs copiously produce radioactive Ni moving outward at fractions of the speed of light. We calculate nuclear abundances of elements accompanying the outflowing Ni under the assumption that this Ni originates from a wind blown off of a viscous accretion disk. We also show that GRB's likely contribute appreciably to the galactic inventory of ^{42}Ca, ^{45}Sc, ^{46}Ti, ^{49}Ti, ^{63}Cu, and may be an important site for the production of ^{64}Zn.

Subject headings: gamma rays: bursts—nucleosynthesis—accretion disks

1. Introduction

In this letter we consider the contribution of Gamma Ray Bursts to the Galactic inventory of some Fe-group elements. Our study is motivated by mounting evidence that a fair fraction of GRB's are associated with the production of a sizable amount of ^{56}Ni moving out with near-relativistic velocities (Price et al. 2003; Stanek et al. 2003; Hjorth et al. 2003; Patat et al. 2001; Iwamoto et al. 1998; Woosley & Heger 2003; Maeda et al. 2003). The ^{56}Fe to which the radioactive Ni decays is not important for the present-day inventory of that element. As we discuss, however, other isotopes synthesized in the unique outflow producing ^{56}Ni likely are important for Galactic chemical evolution.

Though there are other possibilities, we will assume that GRBs are produced by a viscous black-hole accretion disk formed after the collapse of a rotating massive star (Woosley 1993; MacFadyen & Woosley 1999). Within the context of this collapsar model there are

[1]N-Division, Lawrence Livermore National Laboratory, Livermore, CA 94550; pruet1@llnl.gov

[2]Department of Physics, Union College, Schenectady, NY 12308; surmanr@union.edu

[3]Department of Physics, North Carolina State University, Raleigh, NC 27695-8202; Gail_McLaughlin@ncsu.edu

two possible origins for the observed Ni. As in "successful" SNe, Ni may be synthesized explosively as a strong shock traverses the stellar mantle and explodes the star. Maeda & Nomoto (2003) have discussed nucleosynthetic consequences of this picture. Those authors show that a very energetic shock driven by bi-polar jets synthesizes a peculiar abundance pattern that may be responsible for anomalies observed in extremely metal poor stars.

The second possibility is that observed Ni comes from a vigorous wind blown from the accretion disk (MacFadyen 2003; MacFadyen & Woosley 1999). We discuss implications of this scenario, which is qualitatively different from shock-driven nucleosynthesis. Rather than develop a theory describing the disk wind we simply begin with the assumption that a wind is responsible for observed Ni. As we show, this is sufficient to allow interesting statements about nucleosynthesis. However, it should be kept in mind that the origin of the Ni and the nature of the GRB central engine remain uncertain. It should also be emphasized that if a wind is responsible for observed Ni there is likely still interesting explosive nucleosynthesis occurring in the collapsar. Both explosive synthesis and the disk-wind will contribute to enrichment of the interstellar medium.

2. Nuclei Accompanying Ni in a Disk Wind

Nucleosynthesis in the disk-wind is sensitive to the dynamic timescale $\tau_{\rm dyn}$ characterizing the expansion of the wind, the entropy per baryon s in the wind, and the neutron to proton ratio n/p in the wind. To a large degree these parameters are constrained by observation. These constraints follow in part from the observations that Ni is ejected relativistically. Also, the efficiency for Ni production cannot be too low. This is because the disk can eject at most one or two solar masses of fast and initially hot material. In order to account for the $\sim 1/2 M_{\odot}$ of Ni inferred from the light curves of SN1998bw and SN2003dh the mass fraction of Ni in the wind must satisfy $X(^{56}{\rm Ni}) \gtrsim 1/4 - 1/2$ if only one or two solar masses of material is ejected from the disk.

The presence of any ^{56}Ni implies that $Y_e > 0.485$ (Hartmann, Woosley & El Eid 1985). Here the electron fraction $Y_e = p/(n+p)$. A high efficiency for Ni production ($X(^{56}{\rm Ni}) > 0.25$) implies $Y_e \gtrsim 1/2$, with the exact value depending on the other outflow parameters.

Detailed estimates of the electron fraction cannot be made without reference to a specific disk/outflow model. This is because the temperature and density in the disk are high enough that weak interactions determine the composition of the disk (Pruet, Woosley, & Hoffman 2003; Beloborodov 2003; Surman & McLaughlin 2003) and the composition of the wind flowing off the disk. Pruet, Thompson & Hoffman (2003) employed a steady-state wind picture to model the disk outflow and found asymptotic electron fractions anywhere in the range $0.50 - 0.55$, with the value depending sensitively on the accretion rate and viscosity of the disk. Surman & McLaughlin (2003) studied the influence of charged current neutrino capture and found that neutrino capture can increase the electron fraction by a considerable fraction if the neutrino luminosity of the disk is large. Charged current neutrino capture is expected to increase the asymptotic electron fraction in outflows from a "canonical" disk with viscosity $\alpha = 0.1$, mass accretion rate $\dot{M} = 0.1 M_\odot\,\mathrm{sec}^{-1}$ and Kerr parameter $a = 0.95$ by as much as $\delta Y_e \approx 0.05$. For other trajectories/disk models the effect may be larger. The largest Y_e consistent with efficient Ni production is $Y_e \approx 0.60$, with the exact value again depending on other outflow parameters.

Uncertainty in the electron fraction is somewhat of a hindrance to the present study. However, as we will show, certain nuclei will have substantial overproduction factors as long as $0.505 < Y_e$. The special case of $0.50 < Y_e < 0.505$ will be mentioned, but not emphasized because it seems unlikely that the electron fraction in the bulk of the outflow should be within 1% of the minimum value for efficient Ni production. By contrast, in explosive burning Y_e is set not by weak interactions, but by the initial nearly isospin symmetric composition of the burning shell.

To make inferences about the dynamic timescale and entropy in the wind we make the assumption that the wind is coasting at the low temperatures important for nucleosynthesis. The assumption that the wind is not accelerating at $T_9 \equiv T/10^9 K < 5$ seems plausible since an accelerating wind generally expands too quickly for efficient Ni synthesis. Also there is little enthalpy left for driving acceleration at such low temperatures. The great kinetic energy of the wind and small radii at which the wind achieves low temperatures argue that outflows from the disk are not decelerated significantly before nuclear recombination. However, the assumption of a coasting wind will have to be tested against numerical simulations that include expulsion of the stellar mantle in a consistent way.

Mass conservation determines the evolution of coasting winds through $\dot{M} = 4\pi r^2 \rho v_f$, with ρ the density, v_f the asymptotic velocity, and $\dot{M}$ an effective spherical mass outflow rate. For these winds the dynamic timescale is conveniently expressed in terms of the entropy and

$$\beta \equiv \frac{\dot{M}_{-1}}{v_{0.1}^3}. \tag{1}$$

Here $\dot{M}_{-1} = \dot{M}/0.1 M_\odot\,\mathrm{sec}^{-1}$ and $v_{0.1} = v/0.1c$. To make inferences about β and s, note that efficient Ni production implies that $\beta \gtrsim 3$ if $s = 50$ and $\beta \gtrsim 0.6$ if $s = 30$ (see Fig. 3 in Pruet, Thompson & Hoffman (2003)). Also, if the Ni outflow is to be relativistic ($v_{0.1} \gtrsim 1$), β cannot be larger than about 20.

With estimates for Y_e and the expected range of β and s, we can calculate nucleosynthesis in the disk wind. The reaction network used here was developed with proton rich burning in X-ray bursts in mind and has recently been described in Woosley et. al (2003). We use a fixed (rather than adaptive) network that includes elements with $Z = 1 - 52$. For elements with $13 < Z < 41$ we typically include all isotopes with $-30 < Z - N < 9$, which is a large enough network to contain the nuclear flow.

In Fig. 1 we show the results of nucleosynthesis calculations for different assumptions about the wind parameters. These assumptions are thought to approximately bracket the expected range of conditions in those accretion disk outflows that synthesize ^{56}Ni with modest or high efficiencies. The unnormalized overproduction factor for nucleus j is defined here as $X_j/X_{\odot,j}$, where X_j is the mass fraction of the nucleus j in the wind and $X_{\odot,j}$ is the mass fraction of the nucleus in the sun. Though the finer details of nucleosynthesis depend on the wind parameters, there are some interesting features of the nucleosynthesis that do not. In particular, ^{42}Ca, ^{45}Sc, ^{46}Ti, ^{49}Ti, ^{63}Cu, and ^{64}Zn are all produced with large overproduction factors independent of the wind parameters. The abundance pattern is quite different from the abundance yields obtained in an explosive burning scenario (see Table 2). This is not surprising, since relativistic winds and explosive shock-burning are very different events.

The influence of Y_e on the nuclear abundances is addressed in Table 1. In this table production factors for several nuclei are shown for a wind described by $\beta = 4$ and $s = 30$. Here the production factor for nucleus j is defined as

$$O(j) = \frac{M_j}{X_{\odot,j} M^{ej}} = \frac{M^{wind}}{M^{ej}} \frac{X_j}{X_{\odot,j}}, \tag{2}$$

where M_j is the total mass of the nucleus j ejected in the wind, $M^{wind} \approx 1 - 2M_{\odot}$ is the total mass coming from the disk in the form of a wind, and $M^{ej} \sim 10 - 20M_{\odot}$ is the total mass ejected in the supernova explosion.

As can be seen from Table 1, changing Y_e from 0.50 to 0.505 results in dramatic changes in the nucleosynthesis. For $0.51 < Y_e < 0.60$, ^{42}Ca, ^{45}Sc, ^{46}Ti, and ^{49}Ti have production factors that only vary by a factor of approximately two. Production of ^{63}Cu and ^{64}Zn drops markedly with increasing Y_e. The production factors are generally most sensitive to Y_e if weak interactions somehow conspire to set the electron fraction within 1% of $Y_e = 0.50$. As can be seen, an electron fraction very close to 1/2 might have interesting implications for ^{64}Zn.

For definiteness we focus on parameters that are in-between the more extreme cases shown in Fig. 1, such as $s = 30$, $\beta = 4$ and $Y_e = 0.51$. In Table 2 we show the production factors for nuclei synthesized in this wind. For reference and to underscore the importance of a detailed understanding of conditions in collapsar outflows we also show production factors for two somewhat slower winds ($\beta = 16$) with $s = 30$ and $s = 50$. The last column in Table 2 gives production factors for the SN explosion of a $20 M_\odot$ star as calculated by Woosley & Weaver (1995). Note that the production factors for the reference supernova are of order 10, which is the typical value required to explain the presence of nuclei attributed to type II SNe (Mathews, Bazan, & Cowan 1992). By contrast, the production factors for the collapsar wind are 100 or greater in some cases. To connect this with galactic chemical evolution, note that the "SN-equivalent production factor" for collapsars is

$$O^{equiv} \equiv O f_c, \tag{3}$$

where f_c is the fraction of core collapse SNe that become collapsars.

The fraction of SNe that become collapsars is not well known. Observationally, the GRB rate is $\sim 1/100$ the SN rate (e.g. Frail et al. (2001)). This implies the rough lower limit $f_c \gtrsim 0.01$. The true fraction is likely larger because special conditions must be met in order for a collapsar to be observed as a GRB. For example, the hydrogen envelope of the progenitor star must have been blown off in order for a jet to make its way out of the star (i.e. the SN must be type Ib/c). Heger et al. (2003) estimate that f_c could be as large as 0.1 depending on the metallicity and initial mass function for stellar formation.

Nuclei with $O^{equiv} \sim 5 - 10$ will have significant contributions from collapsars. In particular, if $f_c \gtrsim 1/80$ half or more of the galactic abundance of ^{45}Sc will come from collapsars if $O(^{45}\mathrm{Sc} \sim 400)$. If $f_c \gtrsim 0.02 - 0.1$ then the abundances of ^{42}Ca, ^{45}Sc, ^{46}Ti, ^{49}Ti, ^{51}V, ^{63}Cu, and ^{64}Zn can have significant contributions from collapsars. A detailed discussion of implications of nucleosynthesis in collapsars is beyond the scope of this Letter. Here we discuss some interesting implications as can be inferred from the work of Woosley & Weaver (1995) and Timmes, Woosley & Weaver (1995).

^{42}Ca: In SNe this isotope is made during explosive oxygen burning in sufficient quantities to explain the observed solar abundance. ^{40}Ca is about 100 times more abundant than ^{42}Ca in SN ejecta. In the present calculations, however, ^{42}Ca and ^{40}Ca are ejected with similar abundances. Future observation of comparable ^{42}Ca and ^{40}Ca abundances in a metal-poor star might indicate enrichment by a collapsar.

^{45}Sc: This is the only stable Sc isotope. Chemical evolution studies show that at low metallicities Sc is under produced by about a factor of 1.5 relative to observation. Our calculations indicate that collapsars can synthesize sufficient Sc to explain the discrepancy if the electron fraction in the disk wind is larger than about 0.51.

^{49}Ti: This isotope is under produced by about a factor of two in chemical evolution studies. Collapsars can explain the discrepancy if $f_c \sim 1/60$ and $Y_e \gtrsim 0.505$.

^{64}Zn: The origin of this isotope is a mystery since it is under produced by about a factor of 5 in chemical evolution studies. One possible site for the origin of this isotope is the modest entropy early-time neutrino driven wind occurring after core bounce in SNe (Woosley & Hoffman 1992). Collapsars may be another if the electron fraction in the disk wind is less than about 0.51.

In addition to implications for chemical evolution and abundances in metal-poor stars, the scenario we discuss also has implications for the recently observed X-ray emission lines that have been interpreted as iron (e.g. Piro et al. (1999); Antonelli et al. (2000); Piro et al. (2000)). For a review see Boettcher (2002). It has been suggested that these lines may instead be nickel, for example, either nickel produced in the disk that lines the falls of the hole left over from the jet, or small amounts of nickel which have been ejected at rapid velocities behind the jet (McLaughlin, Wijers, Brown, & Bethe 2002; McLaughlin & Wijers 2002). As we have discussed, if a disk wind is responsible for ^{56}Ni production, then Ni is by far the most abundantly produced element in the wind. The second most abundant element (generally Zn) typically contributes at the $\lesssim 5\%$ level. Therefore, if this is the mechanism for producing the observed X-ray line features, one expects initially a strong line or lines from the nickel, with much weaker lines from other elements such as zinc. Explosive burning on the other hand, produces considerable nickel, but also with large mass fractions of light elements such as ^{24}Mg. Such light elements will also be present in the stellar envelope above the wind. Furthermore if both a disk wind and explosive nucleosynthesis occur, then one may be able to observe lines from the combination of elements produced in each.

3. Summary

Observations of ^{56}Ni associated with GRBs hint at the occurrence of a unique nucleosynthesis event. Massive, modest entropy, relativistic winds may be responsible for production of observed Ni. If so, GRBs are important for Galactic chemical evolution and can make important contributions to the abundances of ^{42}Ca, ^{45}Sc, ^{46}Ti, ^{49}Ti, ^{63}Cu, and ^{64}Zn.

JP gratefully acknowledges Stan Woosley for guidance and many helpful suggestions. We are also indebted to Keiichi Maeda for carefully reading the paper and providing many insightful comments. This research has been supported through a grant from the DOE Program for Scientific Discovery through Advanced Computing (SciDAC; DE-FC02-01ER41176). This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract W-7405-ENG-48. GCM acknowledges support from U. S. Department of Energy under grant DE-FG02-02ER41216.

REFERENCES

Anders, E. & Grevesse, N. 1989, Geochimica et Cosmochimica Acta, 53, 197

Antonelli, L. A., et al. 2000, ApJ 545, L39

Beloborodov, A. M. 2003, ApJ, 588, 931

Boettcher, M. 2002, astro-ph/0212034

Frail, D., et al. 2001, ApJ, 562, L55

Hartman, D., Woosley, S. E., & El Eid, M. 1985, ApJ, 297, 837

Heger, A., Fryer, C.L., Woosley, S.E., Langer, N. & Hartmann, D.H. 2003, ApJ, 591, 288

Iwamoto, K. et al. 1998, Nature, 395, 672

Hjorth, J. et al. 2003, Nature, 423, 847

Hoffman, R. D., Woosley, S. E., & Qian, Y.-Z. 1997, ApJ, 482, 951

Inoue, S., Iwamoto, N., Orito, M. & Terasawa, M. 2003, ApJ, 595, 294

Lemoine, M. 2002, A&A, 390, 31L

MacFadyen, A. I. & Woosley, S. E. 1999, ApJ, 524, 262

Macfadyen, A. I. 2003, astro-ph/0301425

Maeda, K. & Nomoto, K. 2003, ApJ, 598, 1163

Maeda, K., Mazzali, P., Deng, J., Nomoto, K. Yoshii, Y., Tomita, H. & Yukiyasu, K. 2003, ApJ, 593, 931

McLaughlin, G. C., Wijers, R. A. M. J., Brown, G. E., & Bethe, H. A. 2002, ApJ, 567, 454

McLaughlin, G. C. & Wijers, R. A. M. J. 2002, ApJ, 580, 1017

Mathews, G. J., Bazan, G., & Cowan, J. J. 1992, ApJ, 391, 719

Nagataki, S., Mizuta, A., Yamada, S., Takabe, H. & Sato, K. 2003, ApJ, accepted

Patat, F. et al. 2001, ApJ, 555, 900

Piro, L., et al. 1999, ApJ 514, L73

Piro, L., et al. 2000, Science 290, 955

Popham, R., Woosley, S. E., & Fryer C. L 1999, ApJ, 518, 356

Price, P. A. et al. 2003, ApJ, 589, 838

Pruet, J., Guiles, S., & Fuller, G. M. 2002, ApJ, 580, 368

Pruet, J., Thompson, T.A. & Hoffman, R.D. 2003, submitted to ApJ

Pruet, J., Woosley, S.E., & Hoffman, R.D. 2003, ApJ, 586, 1254

Stanek, K. Z. et al. 2003, ApJ, 591 L17

Surman, R. & McLaughlin, G. C., 2003, astro-ph/0308004

Timmes, F.X., Woosley, S.E. & Weaver, T.A. 1995, ApJS, 98, 617

Woosley, S.E. & Hoffman, R.D. 1992, ApJ, 395, 202

Woosley, S. E. 1993, ApJ, 405, 273

Woosley, S.E. & Weaver, T.A. 1995, ApJS, 101, 181

Woosley et al., 2003, submitted to ApJ, astro-ph/0307425

Woosley, S. E. & Heger, A. 2003, astro-ph/0309165

This preprint was prepared with the AAS LaTeX macros v5.0.

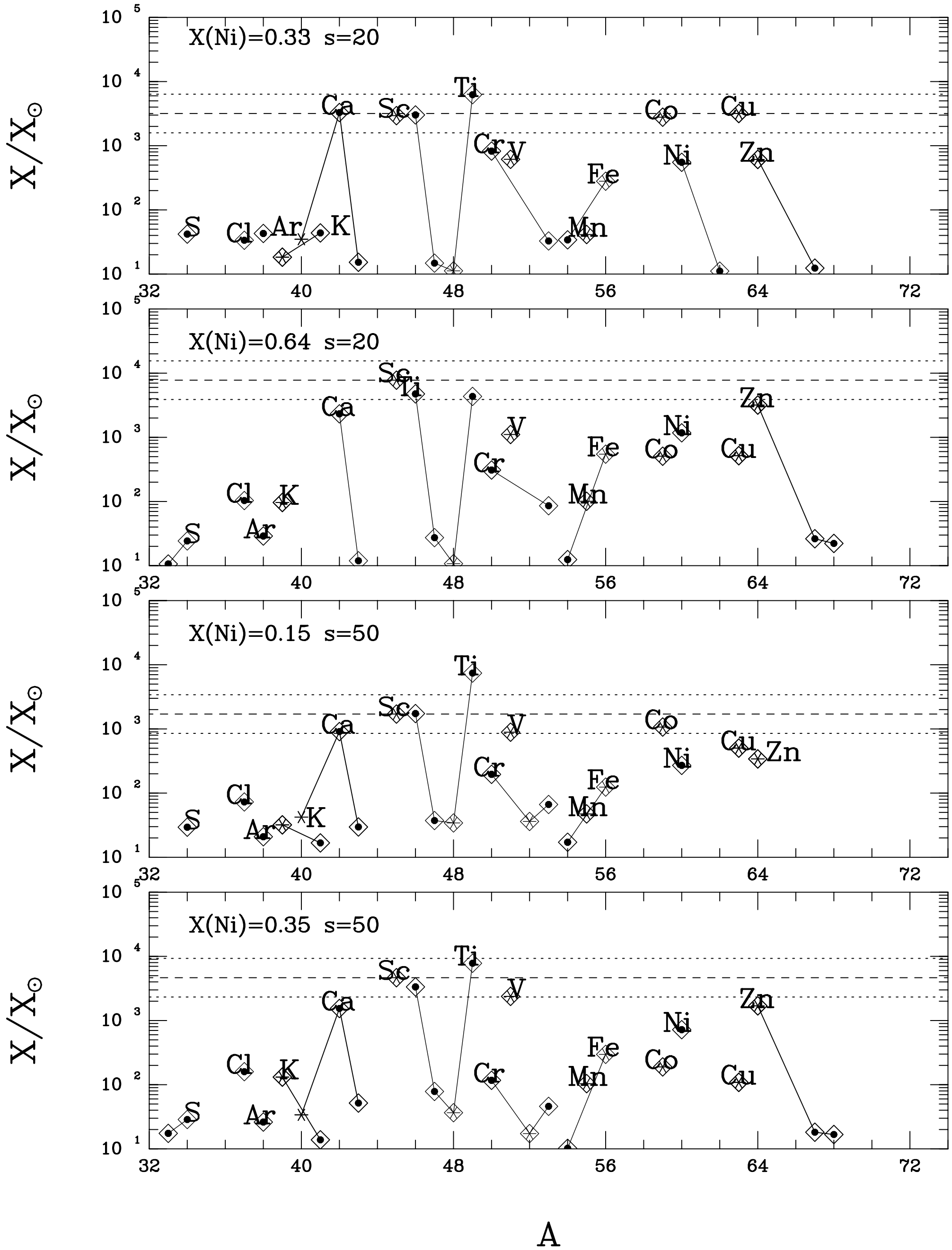

Fig. 1.— Overproduction factors calculated for different accretion disk winds. Solid lines connect isotopes of a given element. The most abundant isotope in the Sun for a given element is plotted as an asterisk. A diamond around a data point indicates the production of that isotope as a radioactive progenitor. Here $X(\mathrm{Ni})$ is the mass fraction of ^{56}Ni in the wind. Results are shown for low entropy ($s/k_b = 20$) winds in the cases of $\beta = 0.25$ and $\beta = 16$ and high entropy ($s = 50$) winds for ($\beta = 1$) and ($\beta = 16$). As can be seen, the production of ^{56}Ni varies with both β and the entropy. For all cases $Y_e = 0.51$. Note that ^{45}Sc, ^{64}Zn and several other Fe-group elements have large overproduction factors in all the wind models.

Table 1. Sensitivity of the production of several isotopes to the electron fraction in the wind[a]

Y_e	$O(^{42}\mathrm{Ca})$	$O(^{45}\mathrm{Sc})$	$O(^{46}\mathrm{Ti})$	$O(^{49}\mathrm{Ti})$	$O(^{63}\mathrm{Cu})$	$O(^{64}\mathrm{Zn})$
0.50	0.1	4	13	75	107	210
0.505	53	120	100	465	70	85
0.51	152	383	175	328	55	95
0.55	172	600	372	262	9	33
0.60	138	492	357	264	3	12

[a]Calculated assuming a total wind mass of $1M_{\odot}$ and a total stellar ejecta mass of $20M_{\odot}$.

Table 2. Dependence of the nucleosynthesis on the wind entropy and dynamic timescale [a]

Nucleus[b]	$O^{c}(\beta=4, s=30)$	$O(\beta=16, s=30)$	$O(\beta=16, s=50)$	References O's[d]
^{37}Cl[25]	6	7	8	13
^{39}K[93]	4	6	7	6
^{42}Ca[0.65]	152	119	77	15
^{45}Sc[100]	383	371	232	5
^{46}Ti[8.0]	175	238	167	11
^{49}Ti[5.5]	328	311	390	7
^{51}V[99.7]	99	98	119	7
^{50}Cr[4.3]	27	12	6	12
^{55}Mn[100]	6	6	5	6
^{56}Fe[92]	17	22	15	5
^{59}Co[100]	55	18	9	7
^{60}Ni[26]	39	50	36	5
^{63}Cu[69]	55	14	5	26
^{64}Zn[49]	95	140	85	3

[a]Calculated assuming a total wind mass of $1M_\odot$ and a total stellar ejecta mass of $20M_\odot$. All results here are for $Y_e = 0.51$.

[b]Values shown in square brackets are the percent contribution of each isotope to the total abundance of that element in the sun (Anders & Grevesse 1989). Only isotopes with a production factor larger than 5 are shown. Nuclei not shown here have production factors smaller than $\sim 1/50$ the production factors of the most overproduced nuclei in the wind.

[c]As a reference point, in this model ^{40}Ca has a production factor of 1.3

[d]For model S25A of Woosley & Weaver (1995)